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(54) **REDUCED VOLTAGE SWING CLOCK DISTRIBUTION**

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(52) **U.S. Cl.**
USPC **327/291**; 327/295; 327/165; 327/259

(58) **Field of Classification Search**
None
See application file for complete search history.

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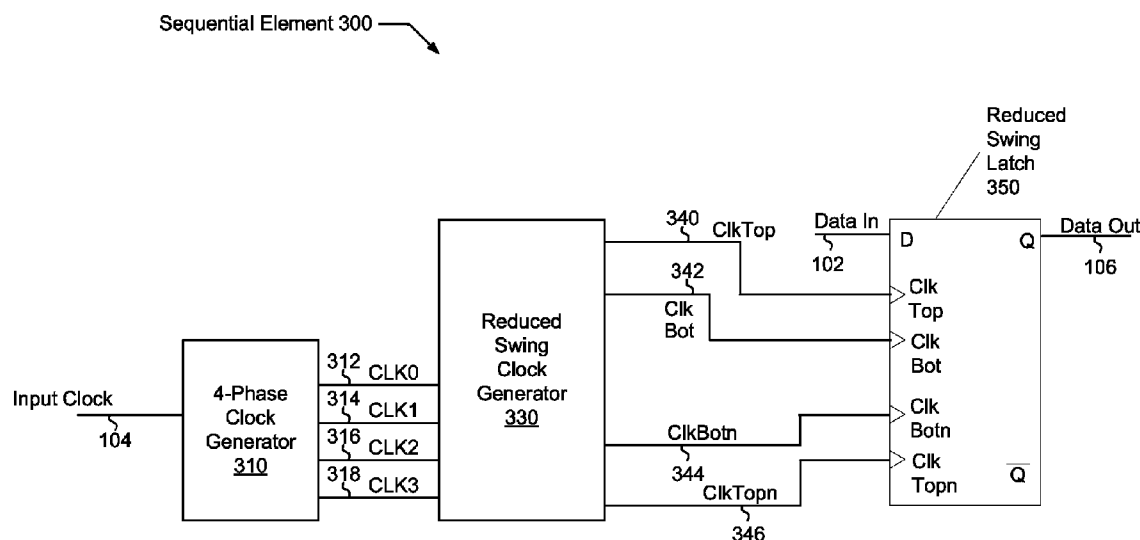
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(57) **ABSTRACT**

A system and method for reducing power consumption within clock distribution on a semiconductor chip. A 4-phase clock generator within a clock distribution network provides 4 non-overlapping clock signals dependent upon a received input clock. A reduced voltage swing clock generator receives the non-overlapping clock signals and charges and discharges a second set of clock lines in a manner sequenced by the non-overlapping clock signals. The sequencing prevents a voltage range from reaching a magnitude equal to a power supply voltage for each of the second set of clock lines. In one embodiment, the magnitude reaches half of the power supply voltage. The reduced voltage swing latch receives the second set of clock lines. The reduced voltage swing latch updates and maintains logical state based at least upon the received second set of clock lines.

25 Claims, 10 Drawing Sheets



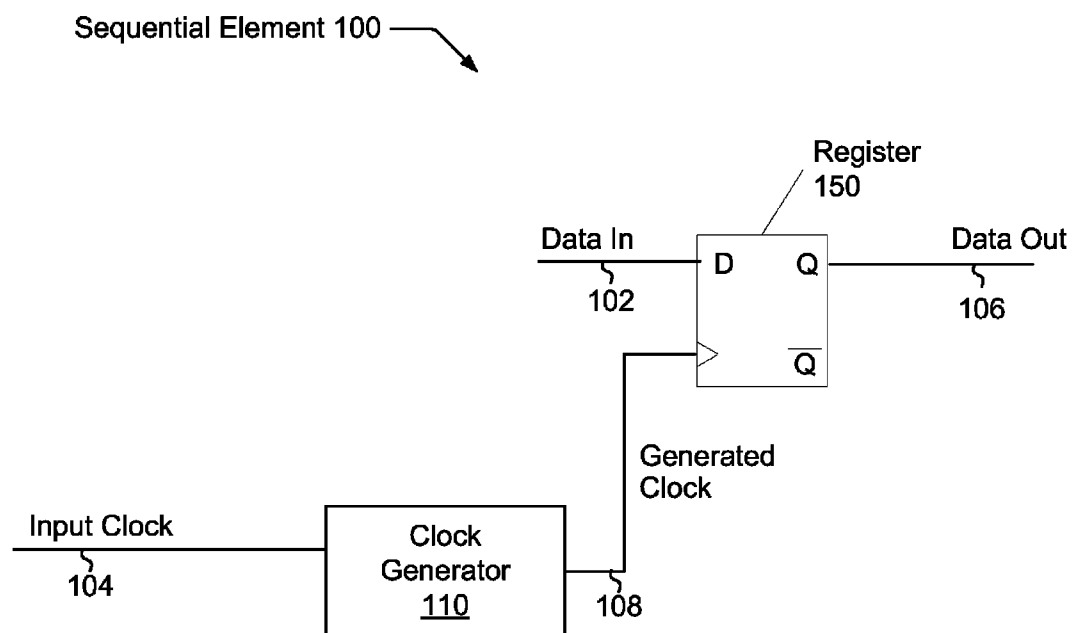


FIG. 1

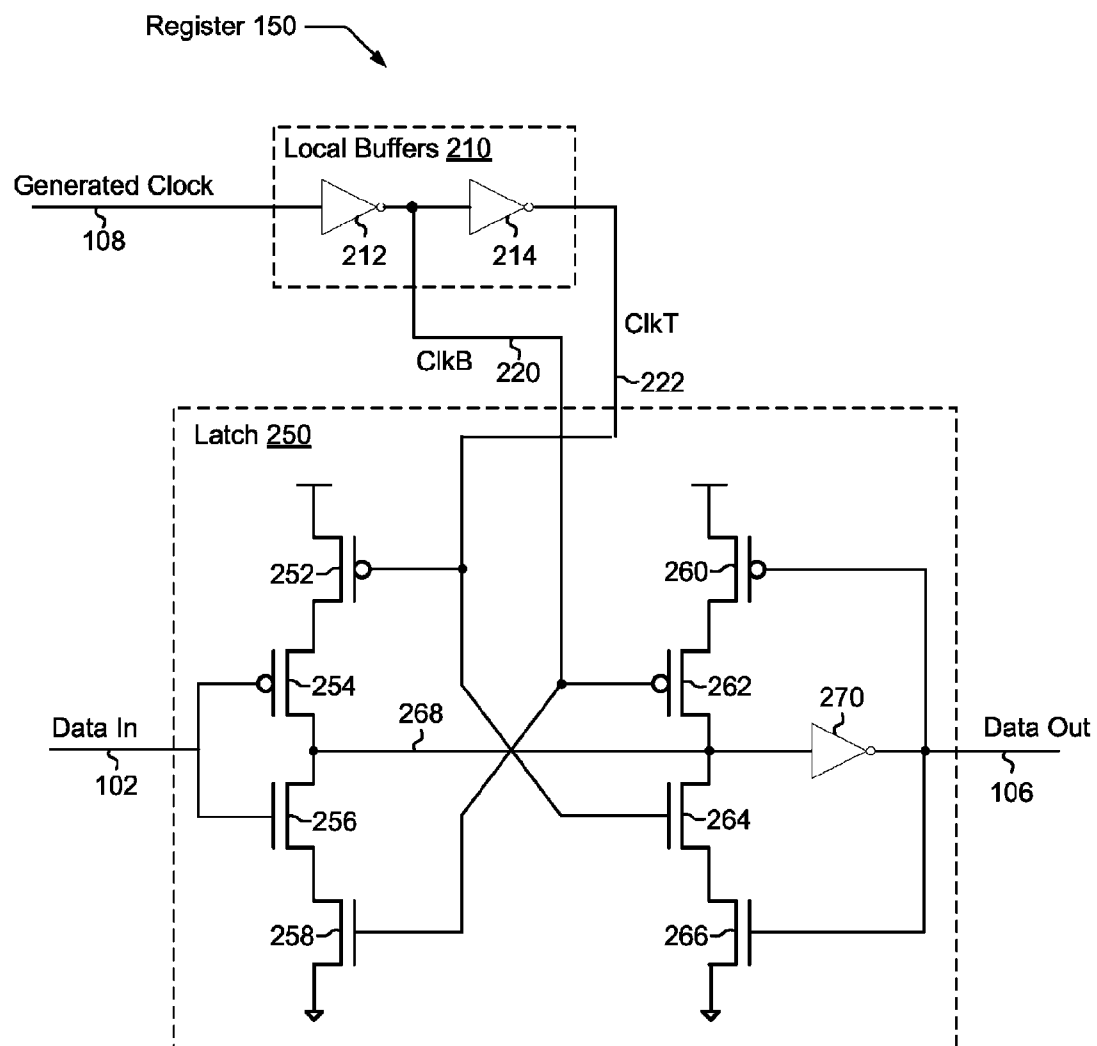


FIG. 2

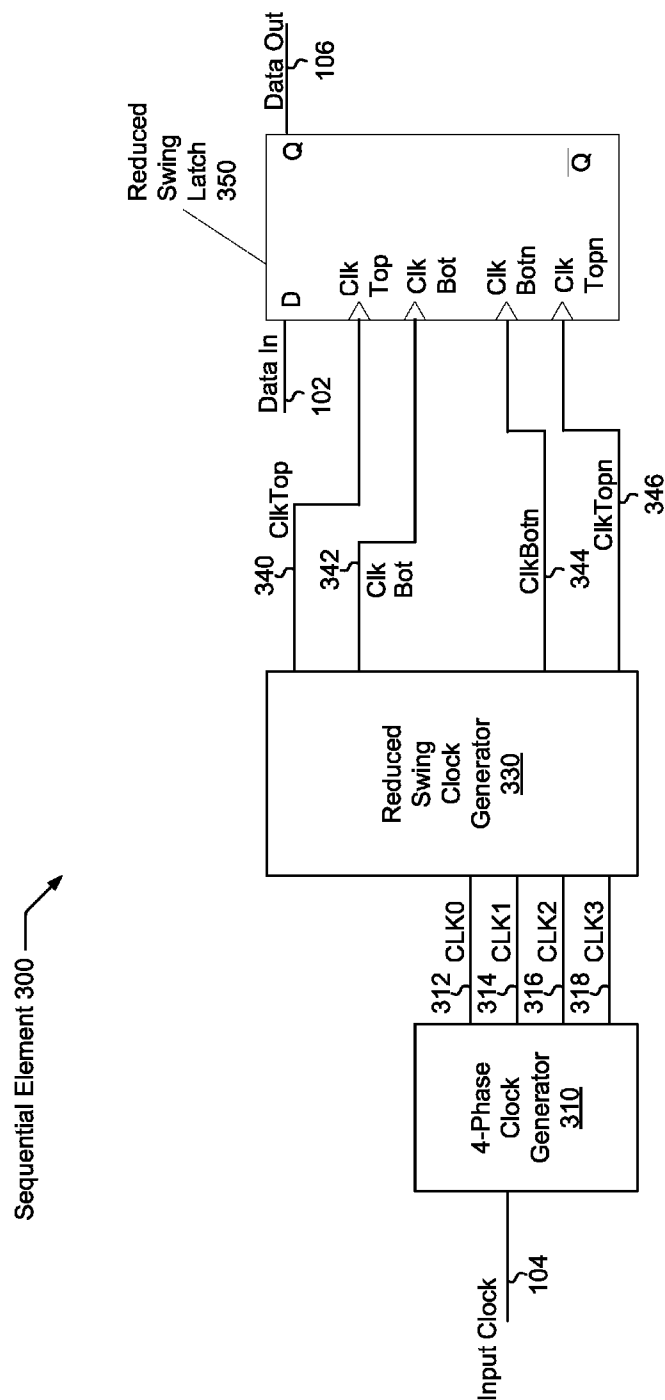


FIG. 3

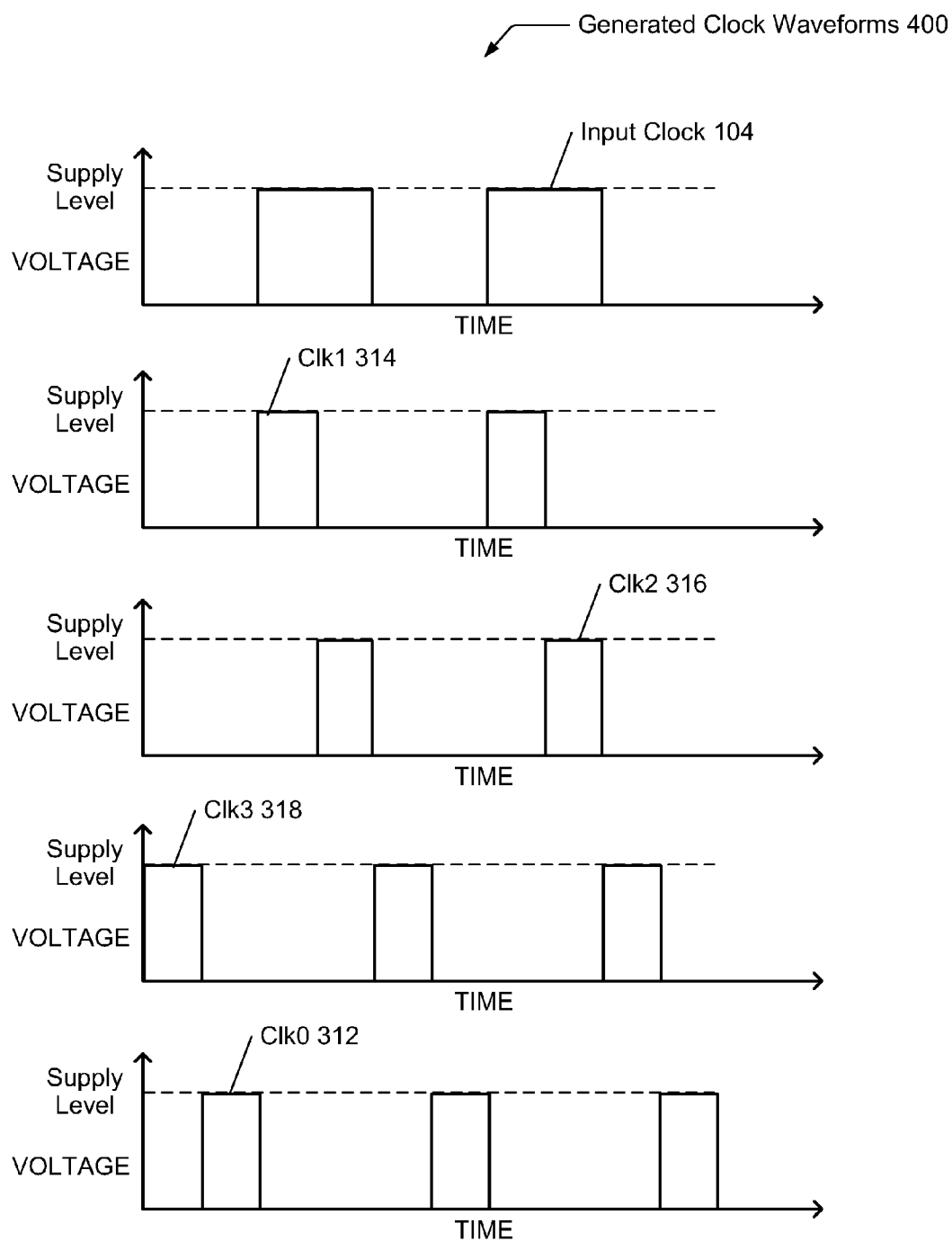


FIG. 4

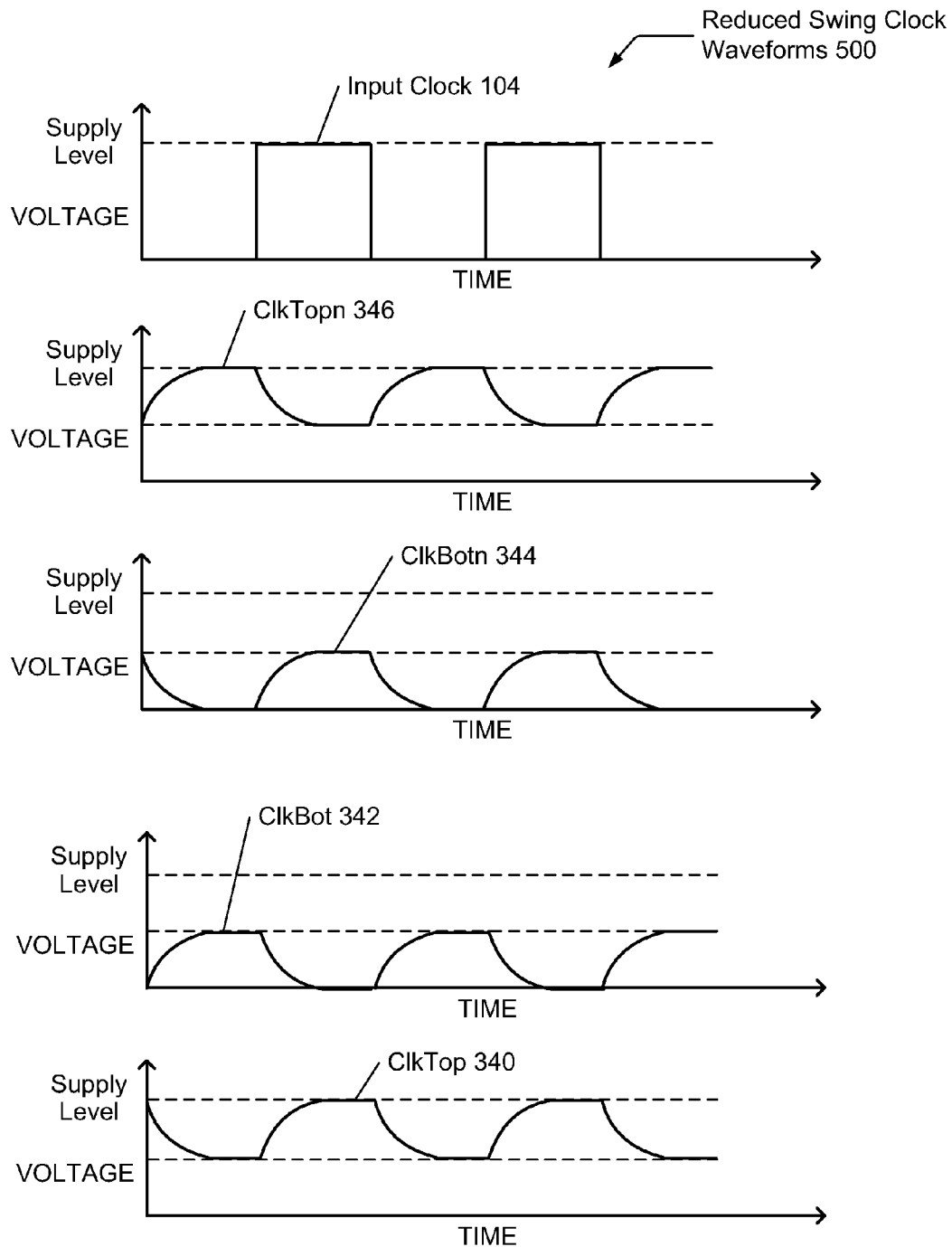


FIG. 5

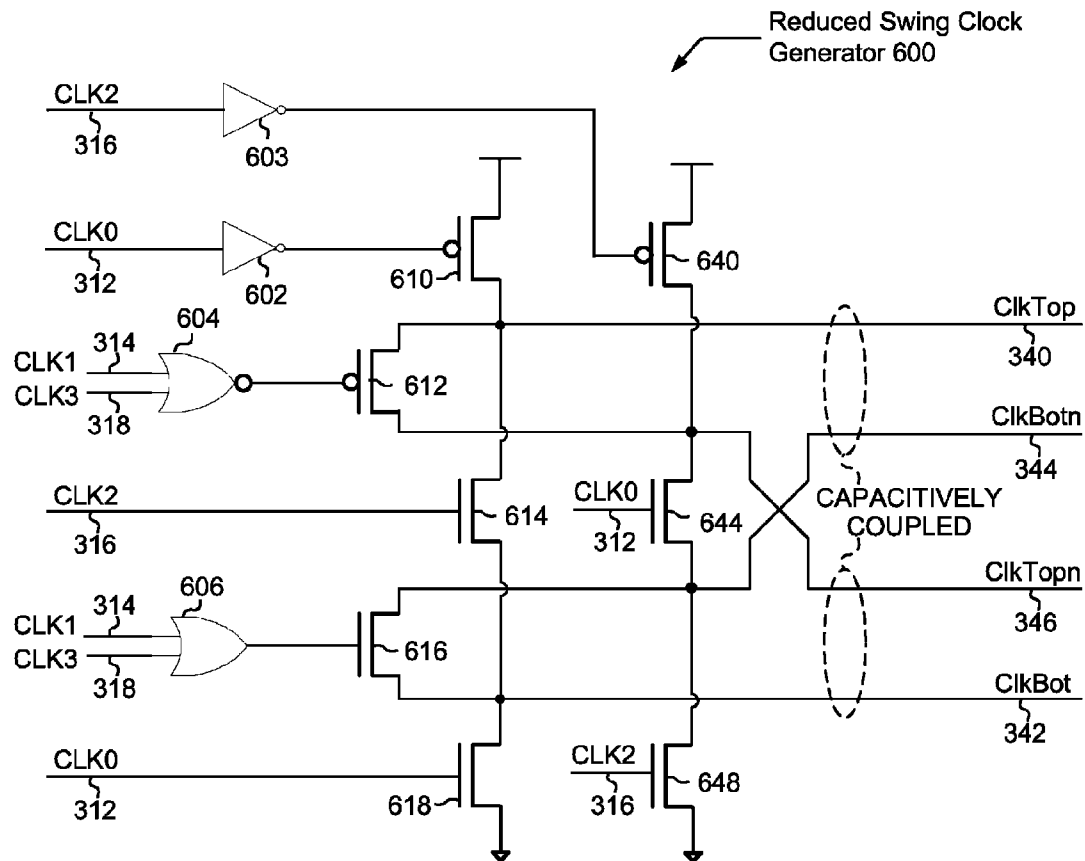


FIG. 6

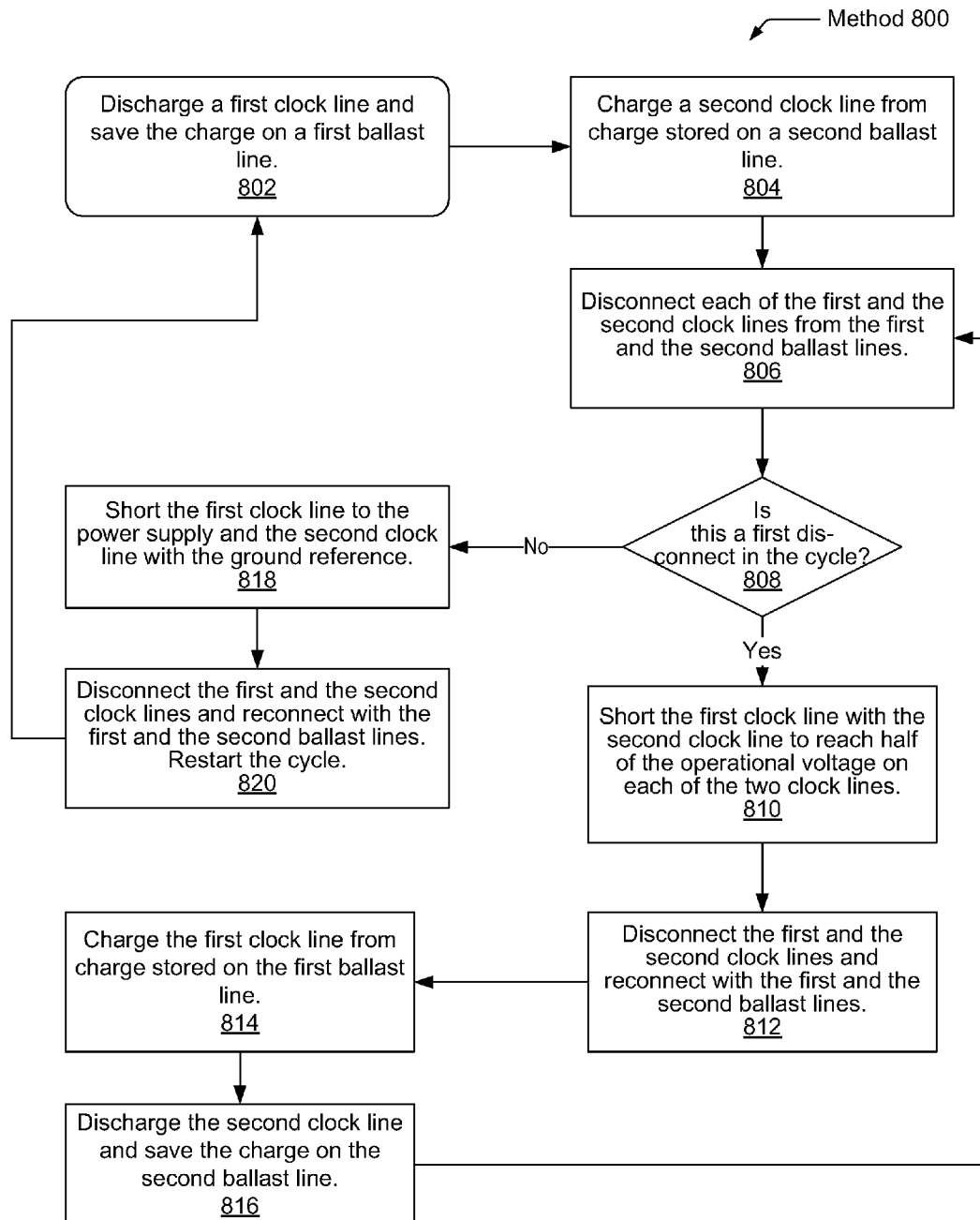


FIG. 7

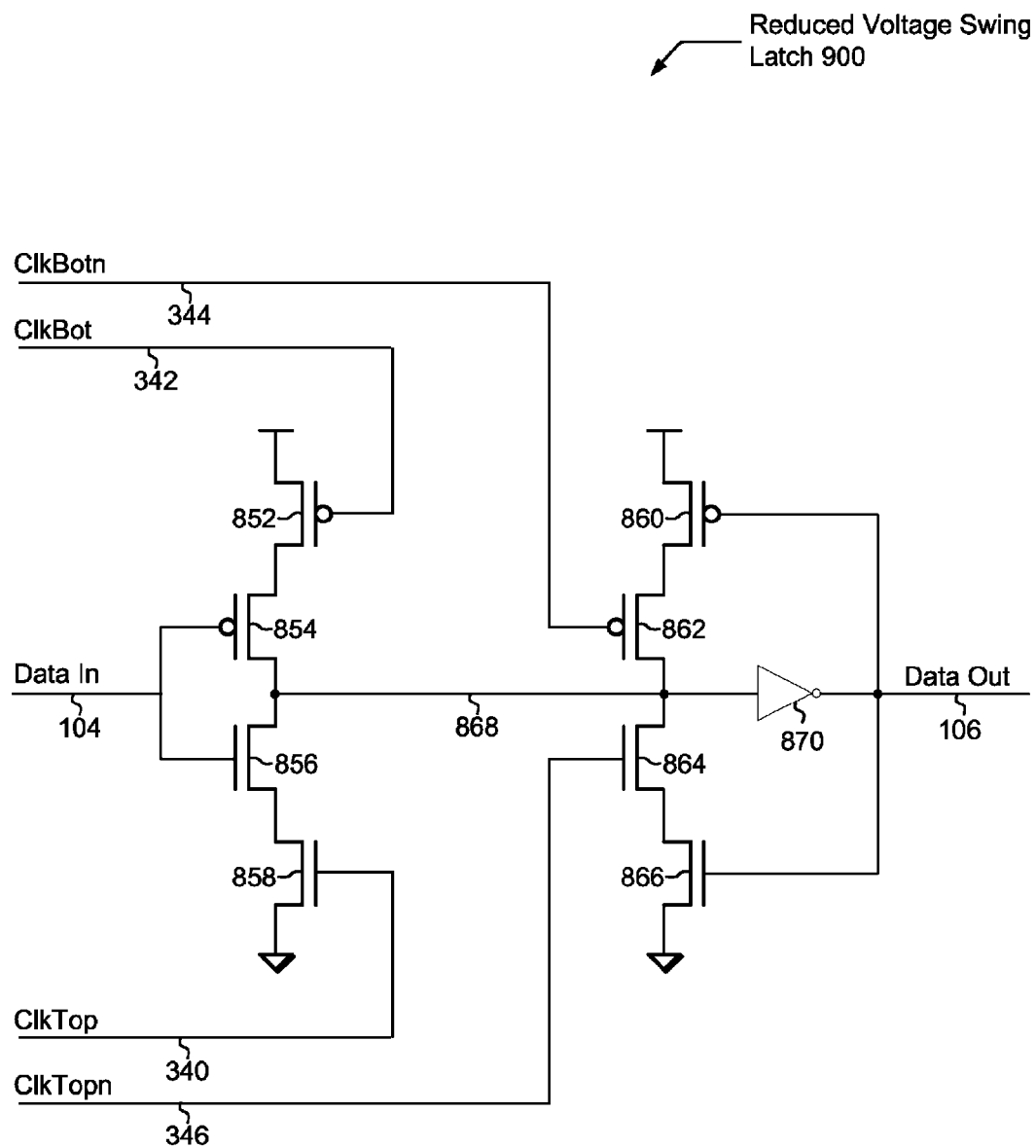


FIG. 8

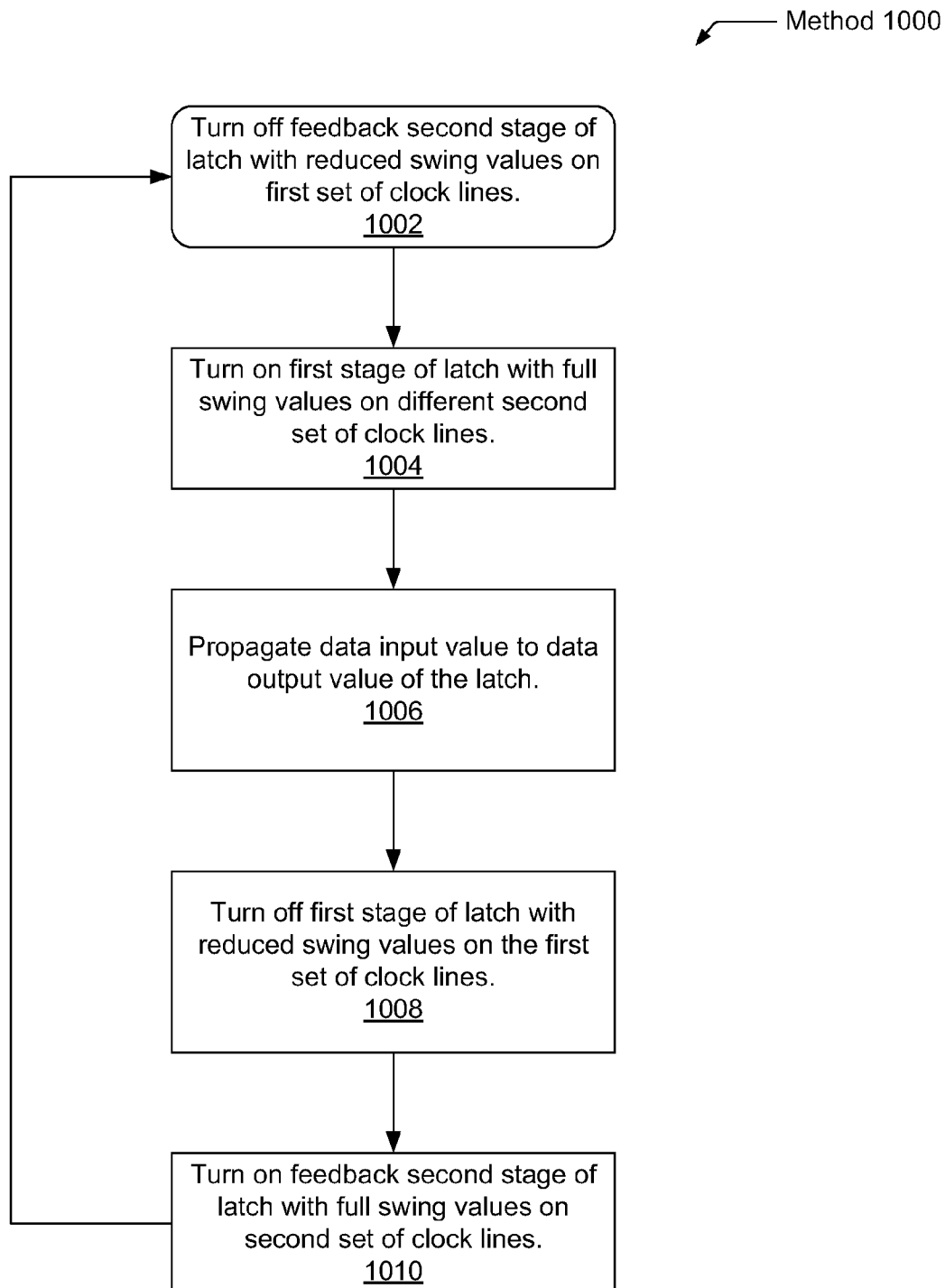


FIG. 9

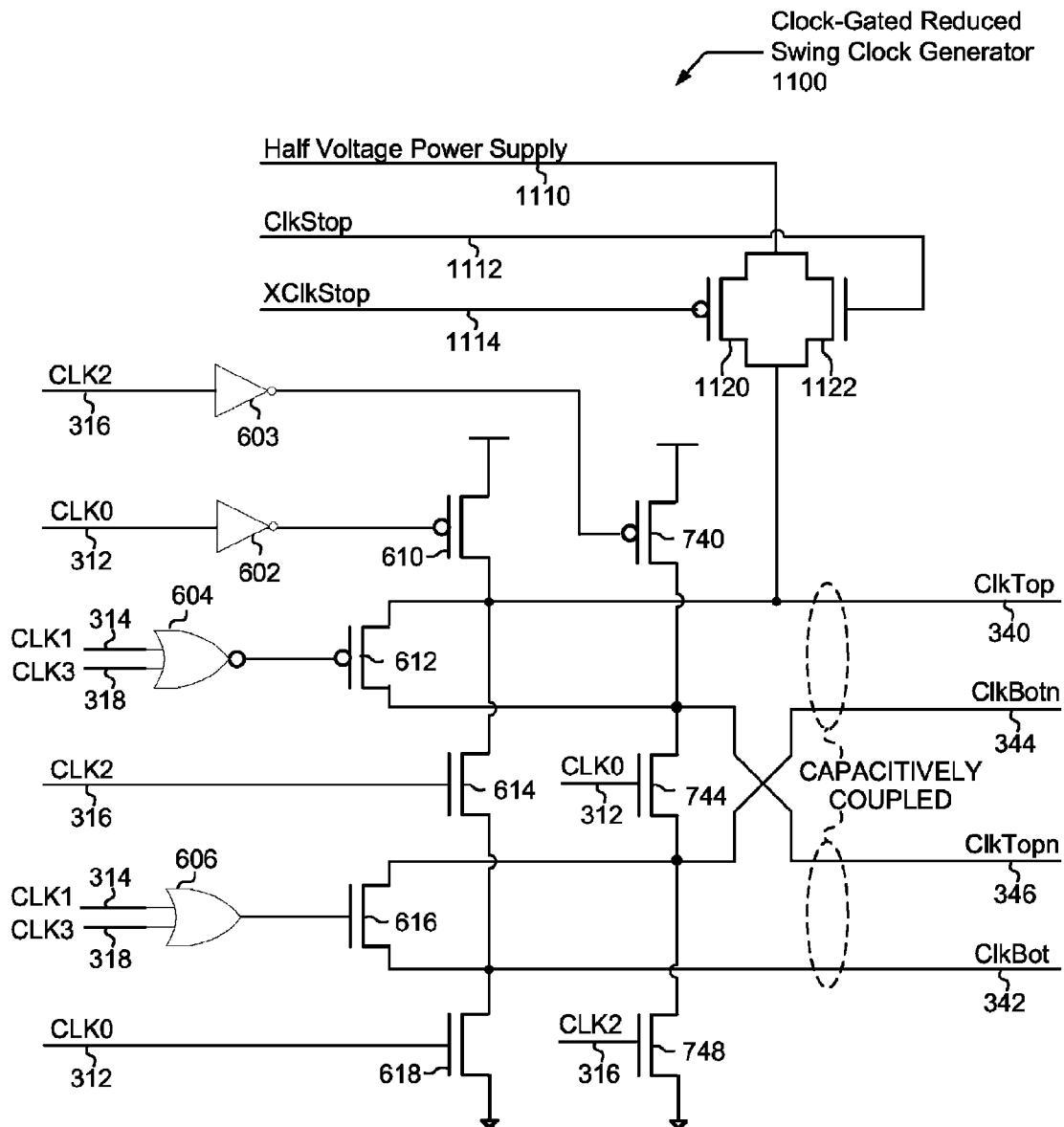


FIG. 10

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REDUCED VOLTAGE SWING CLOCK DISTRIBUTION

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to computing systems, and more particularly, to reducing power consumption within clock distribution on a semiconductor chip.

2. Description of the Relevant Art

Geometric dimensions of devices and metal routes on each generation of semiconductor processor cores are decreasing. Therefore, more functionality is provided within a given area of on-die real estate. As a result, mobile devices, such as laptop computers, tablet computers, smart phones, video cameras, and the like, have increasing popularity. Typically, these mobile devices receive electrical power from a battery. Since batteries have a limited capacity, they are periodically connected to an external charger to be recharged. A vital issue for these mobile devices is power consumption. As power consumption increases, battery life for these devices is reduced and the frequency of recharging increases.

Different power modes supported by a processor core may disable portions of the chip during periods of non-use. This technique may reduce a number of switching nodes and load capacitance being switched. However, associated control logic may become complex and occupy a significant portion of the on-die real estate. Further, multiple executing applications on a mobile device may prevent sufficient disabling to significantly reduce power consumption. Reducing transistor sizes may also reduce an amount of switching capacitance. However, a limit is reached when the transistors already have the minimum available channel width. In addition, leakage current may increase with decreased transistor sizes.

Reducing the operational voltage, V , to decrease power consumption also reduces the amount of current that may flow through a transistor. Thus, the propagation delays increase through transistors. If the threshold voltages are reduced in order to turn-on the transistors sooner and aid in maintaining performance, then transistor current leakage increases, which increases power consumption. A large fraction of the total power consumption may be due to a clock distribution network. In some cases, this large fraction may be as much as half or more of the total power consumption. One or more clock signals are routed to sequential elements and memory structures across the entire die. As these clock signals toggle, buffers within the clock distribution network transition output states, consuming power in the process. Reducing the operational frequency, f , for the chip also reduces the performance of the circuits on the chip. Therefore, this reduction is generally not desirable.

In view of the above, efficient methods and mechanisms for reducing power consumption within clock distribution on a semiconductor chip are desired.

SUMMARY OF EMBODIMENTS OF THE INVENTION

Systems and methods for reducing power consumption within clock distribution on a semiconductor chip. In one embodiment, a reduced voltage swing clock distribution network on a semiconductor chip includes a multi-phase clock generator, a reduced voltage swing clock generator and a reduced voltage swing latch. The multi-phase clock generator provides multiple non-overlapping clock signals dependent upon a received input clock. In one embodiment, each of the non-overlapping clock signals has a same frequency and half

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of the duty cycle of the input clock. The reduced voltage swing clock generator receives the non-overlapping clock signals and charges and discharges a second set of clock lines in a manner sequenced by the non-overlapping clock signals.

The sequencing prevents a voltage range to reach a magnitude equal to a power supply voltage for each of the second set of clock lines. In one embodiment, the magnitude reaches approximately half of the power supply voltage. The reduced voltage swing latch receives the second set of clock lines. The reduced voltage swing latch updates and maintains logical state based at least upon the received second set of clock lines.

These and other embodiments will be further appreciated upon reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a generalized block diagram of one embodiment of a sequential element.

FIG. 2 is a generalized block diagram illustrating one embodiment of a register.

FIG. 3 is a generalized block diagram illustrating another embodiment of a sequential element.

FIG. 4 is a generalized block diagram illustrating one embodiment of generated clock waveforms from a 4-phase clock generator.

FIG. 5 is a generalized block diagram illustrating one embodiment of generated reduced voltage swing clock waveforms from reduced voltage swing clock generators.

FIG. 6 is a generalized block diagram illustrating one embodiment of a reduced voltage swing clock generator.

FIG. 7 is a generalized flow diagram illustrating one embodiment of a method for providing reduced voltage swing clock signals.

FIG. 8 is a generalized block diagram illustrating one embodiment of a reduced voltage swing latch.

FIG. 9 is a generalized flow diagram illustrating one embodiment of a method for latching data values using reduced voltage swing clock signals.

FIG. 10 is a generalized block diagram illustrating one embodiment of a clock-gated reduced voltage swing clock generator.

While the invention is susceptible to various modifications and alternative forms, specific embodiments are shown by way of example in the drawings and are herein described in detail. It should be understood, however, that drawings and detailed description thereto are not intended to limit the invention to the particular form disclosed, but on the contrary, the invention is to cover all modifications, equivalents and alternatives falling within the spirit and scope of the present invention as defined by the appended claims.

As used throughout this application, the word "may" is used in a permissive sense (i.e., meaning having the potential to), rather than the mandatory sense (i.e., meaning must). Similarly, the words "include," "including," and "includes" mean including, but not limited to.

Various units, circuits, or other components may be described as "configured to" perform a task or tasks. In such contexts, "configured to" is a broad recitation of structure generally meaning "having circuitry that" performs the task or tasks during operation. As such, the unit/circuit/component can be configured to perform the task even when the unit/circuit/component is not currently on. In general, the circuitry that forms the structure corresponding to "configured to" may include hardware circuits. Similarly, various units/circuits/components may be described as performing a task or tasks, for convenience in the description. Such descriptions should be interpreted as including the phrase "configured to." Recit-

ing a unit/circuit/component that is configured to perform one or more tasks is expressly intended not to invoke 35 U.S.C. §112, paragraph six interpretation for that unit/circuit/component.

DETAILED DESCRIPTION

In the following description, numerous specific details are set forth to provide a thorough understanding of the present invention. However, one having ordinary skill in the art should recognize that the invention might be practiced without these specific details. In some instances, well-known circuits, structures, and techniques have not been shown in detail to avoid obscuring the present invention.

Referring to FIG. 1, a generalized block diagram illustrating one embodiment of a sequential element 100 is shown. As shown, the sequential element 100 includes a clock generator 110 and a storage element, such as register 150. In one embodiment, the register 150 is a latch storage element. In another embodiment, the register 150 is a flip-flop circuit used as a storage element. In yet another embodiment, the register 150 is a six-transistor (6T) random access memory (RAM) cell used as a storage element. Other implementations of a storage element for register 150 are possible and contemplated. The line Data In 102 receives a data input signal. The line Input Clock 104 receives a clock signal. The register 150 conveys an output value on the Data Out line 106 dependent upon at least a value on the Data In line 102 and an edge or a level of the clock signal on the Input Clock line 104. As used herein, level refers to a voltage level of an associated signal.

An output value on the Data Out line 106 may be sent to combinatorial logic, dynamic logic, another sequential element, and so forth. The sequential element 100 may be used in a variety of embodiments. For example, an apparatus or integrated circuit (IC) including such an element may include a clock distribution network and circuitry. The circuitry may perform a variety of functions such as arithmetic operations, memory access operations, data storage, data conversion, and so forth. The circuitry may perform such functions while using clock signals generated by a clock distribution network that includes the generator 110. In various embodiments, the circuitry may include the register 150 and/or generator 110. Alternatively, the clock distribution network may provide a clock signal to the circuitry. An integrated circuit (IC) may use the sequential element 100. The IC may be any of a variety of IC designs such as a processor, an application specific integrated circuit (ASIC), a core within a processor, an embedded system such as a system-on-a-chip (SOC), a graphics processing unit (GPU), a synchronous memory and so forth. Numerous such embodiments are possible and are contemplated.

Although not shown, the register 150 may include double output lines, feedback circuitry for the input, and scan circuitry. The clock generator 110 may receive a clock signal on the Input Clock line 104 and send a clock signal on the Generated Clock line 108. Although not shown, the clock generator 110 may receive other control signals to affect the signal on the Generated Clock line 108. For example, the clock generator 110 may receive a clock enable signal. Alternatively, clock gating may occur in logic upstream from the clock generator 110 and/or within the register 150.

In one embodiment, the register 150 is a latch. A positive-level latch may be transparent when the received clock signal on the Generated Clock line 108 has a binary high logic value. When the latch is transparent, it transmits values from the Data In line 102 to the Data Out line 106. When the received clock signal on the Generated Clock line 108 has a binary

logic low value, this type of latch is opaque and no data transmission from line 102 to line 106 occurs. For a negative-level latch, the reverse scenario occurs.

In another embodiment, the register 150 is a flip-flop including a master-slave configuration. The master latch and slave latch receive inverted clock signals respective of one another. With a positive-edge triggered embodiment, a master latch is transparent and allows data transmission when the received clock signal on the Generated Clock line 108 has a logic low value. The slave latch is opaque, or closed, during this time and no data transmission to the Data Out line 106 occurs. When the clock signal on the Generated Clock line 108 transitions to a logic high value, the master latch closes and the slave latch opens and becomes transparent allowing data transmission. For a negative-edge triggered flip-flop, the reverse scenario occurs. The register 150 may include pass-gates, or transmission gates, to implement one or more latches. Alternative embodiments may include other transistor topologies such as sense amps, C2MOS topology, dynamic circuits, differential inputs, and other design choices.

Turning now to FIG. 2, a generalized block diagram illustrating one embodiment of the register 150 is shown. Circuitry and logic shown here similar to circuitry and logic described above are similarly numbered. As shown in this embodiment, the local buffers 210 include two inverters 212 and 214 used to buffer the received clock signal on the Generated Clock line 108. The inverter 212 receives the clock signal on the line 108. The inverter 214 receives the output of the inverter 212. Each output of the inverters 212 and 214 is sent to the latch 250. The output of the inverter 212 is sent as ClkB on line 220. The output of the inverter 214 is sent as ClkT on the line 222.

In the embodiment shown, the register 150 is a latch. As described earlier, other embodiments may implement the register 150 as a flip-flop circuit, a RAM cell, and so forth. As shown, the latch 250 includes transistors 254 and 256 connected on the Data In line 102. The transistor 254 is in series with the transistor 252, which has its gate connected to ClkT on line 222. The transistor 256 is in series with the transistor 258, which has its gate connected to ClkB on line 220. Therefore, when the clock signal on the Generated Clock line 108 has a logic low value, the ClkT signal on line 222 also has a logic low value. The ClkB signal on line 220 has a logic high value. During this time, the transistors 252 and 258 are on and an inverted value of a data value on line 102 may be transmitted to the node 268. The logic value on node 268 is inverted and transferred to the Data Out line 106 through inverter 270. When the clock signal on the Generated Clock line 108 has a logic high value, the reverse scenario occurs and the transistors 252 and 258 turn off preventing data transmission from line 102 to node 268.

The transistors 262 and 264 are connected to the node 268. The transistor 262 is in series with the transistor 260, which has its gate connected to the output of the inverter 270 on the Data Out line 106. The transistor 262 has its gate terminal connected to ClkB on line 220. The transistor 264 is in series with the transistor 266, which has its gate connected to the output of the inverter 270 on the Data Out line 106. The transistor 264 has its gate terminal connected to ClkT on line 222. Therefore, when the clock signal on the Generated Clock line 108 has a logic high value, the ClkT signal on line 222 also has a logic high value. The ClkB signal on line 220 has a logic low value. During this time, the transistors 262 and 264 are on and an inverted value of the data value stored on line 106 may be transmitted to the node 268. Thereby, the logic state of the latch 250 is maintained. When the clock signal on

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the Generated Clock line **108** has a logic low value, the reverse scenario occurs and the transistors **262** and **264** turn off preventing data transmission from line **106** to node **268**.

Referring now to FIG. 3, a generalized block diagram illustrating another embodiment of a sequential element **300** is shown. Circuitry and logic shown here similar to circuitry and logic described above are similarly numbered. Similar to sequential element **100**, the sequential element **300** may be used in at least a processor, an ASIC, an SOC, a GPU, a synchronous memory and so forth. Each type of semiconductor chip as listed may include a clock distribution network and circuitry. Generally speaking, the circuitry may include an interface for receiving one or more input clock signals from the clock distribution network, a clock generator for generating one or more additional clock signals based upon the received one or more input clocks, and a reduced voltage swing clock generator. As shown in FIG. 3, the sequential element **300** includes a 4-phase clock generator **310** that generates 4 clock waveforms received by reduced swing clock generator **330**. A reduced voltage swing latch **350** receives the four reduced voltage swing clock waveforms sent by the clock generator **330**. In the illustration shown, a storage element is a latch storage element. In another embodiment, the latch **350** may be replaced with a flip-flop circuit, a six-transistor (6T) random access memory (RAM) cell, or other storage element.

The 4-phase clock generator **310** provides the 4 clock waveforms Clk0 on line **312**, Clk1 on line **314**, Clk2 on line **316** and Clk3 on line **318**. Each of the clock signals on lines **312-318** may have a fraction of the duty cycle of the Input Clock on line **104**, but a same frequency. For example, the Input Clock may have a 50% duty cycle. Each of the clocks signals on lines **312-318** may have a 25% duty cycle. In addition, each of the clock signals on lines **312-318** may be active, or have a high pulse, during a separate portion of the clock cycle.

Based on the clock signals on lines **312-318**, the reduced swing clock generator **330** provides reduced voltage swing clock waveforms. The ClkTop signal on line **340** and the ClkTopn signal on line **346** may have a same frequency as the Input Clock on line **104** and alternate between a half of the supply voltage and a full supply voltage. The ClkTop and ClkTopn signals on lines **340** and **346** may be generated within a top portion of a full voltage swing. In one embodiment, the top portion includes the range between half of the supply voltage and a full supply voltage. Other fractions and endpoints of a full voltage swing that occupy a top portion of the full voltage swing may be chosen based on design tradeoffs. The signals on lines **340** and **346** may be 180 degrees out of phase with one another. Further details are provided shortly.

The ClkBot signal on line **342** and the ClkBotn signal on line **344** may have a same frequency as the Input Clock on line **104** and alternate between a ground reference and a half of the supply voltage. The signals on lines **342** and **344** may be 180 degrees out of phase with one another. The ClkBot and ClkBotn signals on lines **342** and **344** may be generated within a bottom portion of a full voltage swing. In one embodiment, the bottom portion includes the range between the ground reference and half of the supply voltage. Other fractions and endpoints of a full voltage swing that occupy a bottom portion of the full voltage swing may be chosen based on design tradeoffs.

Although not shown, the reduced voltage swing latch **350** may include double output lines, feedback circuitry for the input, and scan circuitry. The reduced swing clock generator **330** may receive other control signals to affect the signals on

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lines **340-346**. For example, the reduced swing clock generator **330** may receive a clock enable signal. The reduced voltage swing latch **350** may receive the clock signals on lines **340-346**. The latch **350** may maintain a state dependent on these clock signals and the data signal received on the Data In line **102**. Selected nodes within the latch **350** may have a reduced voltage clock swing whereby certain nodes transition between a ground reference and half of the supply voltage and certain nodes may transition between half of the supply voltage and the full supply voltage. Selected other nodes may have a traditional full voltage clock swing. Examples of nodes that utilize a reduced voltage swing include at least the inputs that receive the clock signals on lines **340-346**.

In one embodiment, clock signals on lines **340-346** with a reduced voltage swing are received on gate terminals of transistors which may have a relatively high threshold. For example, an n-type field effect transistor (nfet) may receive on its gate terminal the ClkTop signal on line **340** or the ClkTopn signal on line **346**. This nfet may have a threshold voltage value within the top portion of the full voltage swing. This nfet may have a threshold voltage between half of the voltage supply and the full voltage supply. Similarly, a p-type field effect transistor (pfet) may receive on its gate terminal the ClkBot signal on line **342** or the ClkBotn signal on line **344**. This pfet may have a relatively high threshold voltage. As noted, although some nodes within the latch **350** there utilize a reduced voltage swing, other nodes within the latch **350** may utilize a full voltage swing. Examples of nodes that utilize a full voltage swing include at least the input that receives the data input signal **102** and the output that provides the data output signal **106**. Additionally, one or more other internal nodes within the latch **350** may utilize a full voltage swing.

The power consumption of modern complementary metal oxide semiconductor (CMOS) chips is proportional to the expression $\alpha f C V^2$, where the symbol α is the switching factor, or the probability a node will charge up or discharge during a clock cycle; f is the operational frequency of the chip; C is the equivalent load capacitance to be charged or discharged in a clock cycle; and the symbol V is the operational voltage of the chip. In order to reduce power consumption, one or more of these parameters may be reduced. By using half of the voltage swing within the reduced swing clock generator **330** and within the latch **350**, the term V^2 reduces the power consumption on given nodes to one quarter of the original power.

Turning now to FIG. 4, a generalized block diagram illustrating one embodiment of generated clock waveforms **400** from the 4-phase clock generator is shown. As described above, the 4-phase clock generator **310** may use the Input Clock on line **104** as a timing reference to create the clock waveforms Clk0 on line **312**, Clk1 on line **314**, Clk 2 on line **316** and Clk3 on line **318**. Each of the clock signals on lines **312-318** may have a fraction of the duty cycle of the Input Clock on line **104**, but a same frequency.

One embodiment of the timing relationships between the Input Clock on line **104** and the clock signals on lines **312-318** is shown in the waveforms **400**. The rising edge of Clk1 on line **314** is approximately coincident with the rising edge of the Input Clock on line **104**. The Clk2 on line **316** may have a phase delay of one-quarter clock cycle from the Clk1. The Clk3 on line **318** may lag the Clk2 by one quarter of a clock cycle. The Clk0 on line **312** may lag Clk3 by one-quarter of a clock cycle. Therefore, in one embodiment, each of the clock signals on lines **312-318** is phase shifted 90 degrees from a phase reference of a previous one of the clock signals on lines **312-318**.

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Turning now to FIG. 5, a generalized block diagram illustrating one embodiment of generated reduced voltage swing clock waveforms 500 from the reduced voltage swing clock generator is shown. As described above, the reduced voltage swing clock generator 330 may use the clock signals on lines 312-318 as timing references to create the reduced voltage swing clock signals ClkTop on line 340, ClkBot on line 342, ClkBotn on line 344, and ClkTopn on line 346.

Each of the clock signals on lines 340-346 may have a same duty cycle of the Input Clock on line 104 and a same frequency. The clock signals ClkTop and ClkBotn on lines 340 and 344 may have a rising edge approximately coincident with the rising edge of the Input Clock on line 104. The clock signals ClkBot and ClkTopn on lines 342 and 346 may have a rising edge approximately coincident with the falling edge of the Input Clock on line 104. Therefore, a first half of the clock signals on lines 340-346 are 180 degrees out of phase with a second half of the clock signals on lines 340-346.

A magnitude of the voltage range of each of the clock signals on lines 340-346 may be a fraction of the power supply voltage, or the operational voltage. Each of the clock signals ClkTop and ClkTopn on lines 340 and 346 may have a voltage range between a given voltage level and an intermediate value between the power supply voltage and the ground reference. In one embodiment, the given voltage level may be the power supply voltage. Alternatively, the given voltage level may be a voltage value near the power supply voltage. The given voltage level may not actually reach the power supply voltage.

Continuing with the voltage range, in one example, the given voltage level may be designed to be a majority fraction of the power supply voltage. In one such example, the given voltage level may be 90% of the power supply voltage. Other fractional values are possible and contemplated. In one embodiment, a selection for a value of the given voltage level may be based on a threshold voltage for a high threshold transistor, an acceptable level of performance for a transistor operating with the given voltage level on its gate terminal rather than the power supply voltage and so forth.

Each of the clock signals ClkBot and ClkBotn on lines 342 and 344 may have a voltage range between the intermediate value and another given voltage level. In one embodiment, the other given voltage level may be a ground reference. Alternatively, the other given voltage level may be a voltage value near the ground reference. Similar to the above discussion for the given voltage level being at or near the power supply voltage, a selection for the value of this other given voltage level may be based on several criteria including operation of a transistor receiving the given voltage level.

In one embodiment, a magnitude of the voltage range of each of the clock signals on lines 340-346 may be one-half of the power supply voltage, or operational voltage. Therefore, in this embodiment, the intermediate value is half of the power supply voltage. In other embodiments, the intermediate value may be a different fraction of the power supply voltage. As described above, the amount of power consumed to charge a capacitance on the chip is proportional to the square of the operational voltage. Therefore, when the intermediate value is half of the power supply voltage, an amount of power consumed to generate the clock signals on lines 340-346 may be approximately one-fourth of the power consumed to generate clock signals with a full voltage swing.

The circuit description provided by FIG. 6 illustrates an embodiment for a reduced swing clock generator that provides at least four reduced swing clock signals. Two of the four generated clock signals in this example are complements of the other two generated clock signals. For example, the

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reduced swing clock signals ClkTop and ClkBot on lines 340 and 342 are generated. In addition, their complement clock signals ClkTopn and ClkBotn on lines 346 and 344 are generated. Other examples of circuit designs used to generate complements of generated reduced swing clock signals are possible and contemplated. Further details of the circuit design for generating reduced swing clock signals and their complements are provided below.

Referring now to FIG. 6, a generalized block diagram of one embodiment of a reduced voltage swing clock generator 600 is shown. The clock signals Clk0 on line 312, Clk1 on line 314, Clk2 on line 316 and Clk3 on line 318 are received by the clock generator 600 and used to produce the reduced voltage swing clock signals ClkTop on line 340 and ClkBot on line 342 and additionally their complement signals ClkTopn and ClkBotn on lines 346 and 344. The load capacitance on each of the clock lines 340 and 342 may include the wire capacitance, the drain capacitances of transistors used to generate the clock signals and the gate capacitances of transistors within sequential elements used to receive the clock signals.

In one embodiment, each of the clock lines 340 and 342 may be routed and connected to have a ratio of load capacitances equal to a ratio of the intermediate value to a difference between the intermediate value and the power supply voltage. The ratio of the load capacitances may be used to provide an intermediate value on each of the clock lines 340 and 342 when these clock lines are shorted together. In one embodiment, the load capacitance of each of the lines 340 and 342 may be made the same. Therefore, when the clock lines are shorted together, the intermediate value may be half of the power supply voltage due to conservation of charge on the lines 340 and 342. In addition, the signal ClkBotn on line 344 may be capacitatively coupled to ClkTop on line 340. The wire routing for ClkBotn on line 344 may follow the wire routing of ClkTop on line 340 with a minimal spacing between the routes. The signal ClkTopn on line 346 may be similarly capacitatively coupled to signal ClkBot on line 342.

Initially, ClkTop on line 340 and ClkBotn on line 344 may have a logic high value. A logic high value for ClkTop on line 340 may be the power supply voltage. A logic high value for ClkBotn on line 344 may be an intermediate voltage level, such as half of the power supply voltage. The signal ClkBot on line 342 and ClkTopn on line 346 may have a logic low value. A logic low value for ClkBot on line 342 may be the ground reference. A logic low value for ClkTopn on line 346 may be the intermediate voltage level, such as half of the power supply voltage. Referring again to FIG. 4, the rising edge of Input Clock on line 104 may trigger Clk1 on line 314 to rise to a logic high value. In the reduced voltage swing clock generator 600, the signal Clk1 is received by both a binary NOR gate 604 and a binary OR gate 606. The transistor 612 receives the output of the NOR gate 604. The transistor 616 receives the output of the OR gate 606. The rise of Clk1 causes both transistors 612 and 616 to turn on.

As transistor 612 turns on, ClkTop on line 340 is shorted to ClkTopn on line 346. At this time, electrical charge is shared between ClkTop on line 340 and ClkTopn on line 346. Initially, ClkTop may have a higher voltage level than ClkTopn. For example, ClkTop may have an initial value of the power supply voltage and ClkTopn may have an initial value of the intermediate voltage, such as half of the supply voltage. Therefore, the voltage for ClkTop on line 340 may drop and the voltage on ClkTopn on line 346 may rise.

Approximately one-quarter of a clock cycle later, the signal Clk1 on line 314 falls to a logic low value, which turns off transistors 612 and 616. At approximately the same time, the signal Clk2 on line 316 rises to a logic high value. The gate

terminal of transistor **614** receives the signal Clk2 on line **316**. In addition, the transistor **648** receives on its gate terminal the signal Clk2 on line **316**. The transistor **640** receives on its gate terminal an inverted value of Clk2. The inverter **603** may invert the signal Clk2 for the transistor **640**. As transistor **614** turns on, ClkTop on line **340** is shorted to ClkBot on line **342**. In addition, as transistor **640** turns on, ClkTopn on line **346** is shorted to the power supply voltage.

As transistor **648** turns on, ClkBotn on line **344** is shorted to the ground reference. Each of the clock lines **340** and **342** may not be connected to either the power supply voltage or the ground reference. At this time, electrical charge is shared between ClkTop on line **340** and ClkBot on line **342**. In one embodiment, the total load capacitance on each of the lines **340** and **342** may be the same. Accordingly, the signals ClkTop and ClkBot may reach a voltage level of approximately one-half of the power supply. In other embodiments, the ratio of the load capacitances on lines **340** and **342** may have different values that create an intermediate voltage value that is different than one half of the power supply voltage.

At the falling edge of Input Clock on line **104**, the signal Clk2 on line **316** may fall to a logic low value and signal Clk3 on line **318** may rise to a logic high value. Similar to the signal Clk1 on line **314**, the signal Clk3 on line **318** is received by both the binary NOR gate **604** and the binary OR gate **606**. Therefore, transistors **614**, **640** and **648** may turn off and transistors **612** and **616** may turn on.

When the transistor **612** turns on, ClkTop on line **340** is once again shorted to ClkTopn on line **346**. At this time, electrical charge is shared between ClkTop on line **340** and ClkTopn on line **346**. The signal ClkTop may have half of the supply voltage on line **340** due to being previously shorted with ClkBot on line **342**. The signal ClkTopn may have a logic high value due to being previously shorted to the power supply voltage. Therefore, the voltage for ClkTop on line **340** may rise and the voltage on ClkTopn on line **346** may drop.

When transistor **616** turns on, ClkBotn on line **344** is shorted to ClkBot on line **342**. At this time, electrical charge is shared between ClkBotn on line **344** and ClkBot on line **342**. The signal ClkBotn may have a logic low value due to being previously shorted with the ground reference. The signal ClkBot may have half of the supply voltage on line **342** due to being previously shorted with ClkTop on line **340**. Therefore, the voltage for ClkBotn on line **344** may rise and the voltage on ClkBot on line **342** may drop.

The inverter **602** and the transistors **618** and **644** may receive the signal Clk0 on line **312**. The transistor **610** may receive the output of the inverter **602** on its gate terminal. At the end of the clock cycle, the signal Clk0 on line **312** may rise. As a result, the transistors **610**, **618** and **644** turn on.

As transistor **610** turns on, ClkTop on line **340** is charged up due to being shorted to the power supply. ClkTop on line **340** may already have a value close to the power supply voltage due to acquiring charge from ClkTopn on line **346** when Clk3 on line **318** had a logic high value. Accordingly, an amount of energy sourced from the power supply to completely charge ClkTop on line **340** may be reduced. Thereby, an amount of power consumed by the clock distribution system may also be reduced.

The transistor **614** is turned off, so ClkBot on line **342** is not shorted to the power supply. As transistor **618** turns on, ClkBot on line **342** is shorted to the ground reference and its value falls to a logic low value. The power savings within the clock generator **600** may be additionally due to the charge from ClkTop on line **340** is temporarily stored in ClkTopn on line **346** when ClkTop on line **340** is discharged. This stored charge is used later in the clock cycle to assist in re-charging

ClkTop on line **340**. Therefore, less energy is utilized by the power supply to re-charge ClkTop on line **340**. A similar mechanism is utilized for the signals on lines **342**, **344** and **346**.

As transistor **644** turns on, ClkBotn on line **344** is shorted to ClkTopn on line **346**. Each of the clock lines **344** and **346** may not be connected to either the power supply voltage or the ground reference. At this time, electrical charge is shared between ClkBotn and ClkTopn on lines **344** and **346**. In one embodiment, the total load capacitance on each of the lines **344** and **346** may be the same. Accordingly, the signals ClkBotn and ClkTopn may reach a voltage level of approximately one-half of the power supply. In other embodiments, the ratio of the load capacitances on lines **344** and **346** may have different values that create an intermediate voltage value that is different than one half of the power supply voltage. As described above, each of the reduced swing clock signals ClkBotn on line **344** and ClkTopn on line **346** may be used as ballast lines to generate complements of the ClkTop and ClkBot signals on lines **340** and **342** and vice-versa.

Turning now to FIG. 7, a generalized flow diagram illustrating one embodiment of a method **800** for providing reduced voltage swing clock signals is shown. For purposes of discussion, the steps in this embodiment and subsequent embodiments of methods described later are shown in sequential order. However, in other embodiments some steps may occur in a different order than shown, some steps may be performed concurrently, some steps may be combined with other steps, and some steps may be absent.

In block **802**, a first clock line initially has a logic high value and it is discharged. A first ballast line saves the charge removed from the first clock line. In block **804**, a second clock line initially has a logic low value and it is charged from charge stored on a second ballast line. In one embodiment, the first clock line is capacitatively coupled to the second ballast line and the second clock line is capacitatively coupled to the first ballast line. Further, each of the first and the second clock lines may be made to have a same load capacitance including wire and gate capacitance. In block **806**, each of the first and the second clock lines may be disconnected from the first and the second ballast lines. In one embodiment, the transitions to connect and disconnect the first and the second clock lines are dependent on a sequencing of received non-overlapping clock signals. Each of the non-overlapping clock signals may have a duty cycle smaller than half of the clock cycle.

If this is a first disconnect with the ballast lines in the cycle (conditional block **808**), then in block **810**, the first clock line may be shorted with the second clock line. Charge is shared on both clock lines and each of the clock lines may reach a value equal to half of the operational voltage. Therefore, the first clock line was discharging from a logic high value, but stopped at half of the operational voltage, rather than falling to the ground reference. Similarly, the second clock line was rising from a logic low value, but stopped at half of the operational voltage, rather than rising to the power supply value. Each of the clock lines experienced a reduced voltage swing, rather than a full voltage swing. In one embodiment, the connections and disconnections of the clock lines with other lines such as each other and the ballast lines is done with transistors being turned on and off in a given sequence.

In block **812**, the first and the second clock lines may be disconnected from one another and reconnected with the first and the second ballast lines. In block **814**, the first clock line may be charged from charge stored on the first ballast line. In block **816**, the second clock line may be discharged and the removed charge may be saved on the second ballast line. Each of the first and the second clock lines are returning to their

original values, but each is not consuming energy for a full voltage swing. Control flow of method **800** may return to block **806**. Each of the first and the second clock lines may be disconnected from the first and the second ballast lines.

If this is not a first disconnect with the ballast lines in the cycle (conditional block **808**), then in block **818**, the first clock line may be shorted to the power supply and the second clock line may be shorted with the ground reference. Each of the clock lines may reach full initial values equivalent to the power supply value and the ground reference, respectively. In block **820**, the first and the second clock lines may be disconnected from one another and reconnected with the first and the second ballast lines. Control flow of method **800** returns to block **802** and the process repeats. The sequence of connections and charging and discharging of the lines may provide two clock waveforms with a reduced voltage swing. In some embodiments, the first and the second ballast lines may be used as complements to the two reduced voltage swing clock signals. For example, a circuit as shown in FIG. **6** and described above may be used. In some embodiments, an intermediate voltage level other than half of the power supply voltage may be used.

Referring now to FIG. **8**, a generalized block diagram illustrating one embodiment of a reduced voltage swing latch **900** is shown. Circuitry and logic shown here similar to circuitry and logic described above are similarly numbered. Although a latch is shown, the principles applied to latch **900** may be applied to a flip-flop or other storage elements. The transistors **852-866** may use a same topology as transistors **252-266** in latch **250**. However, transistors **852, 858, 862** and **864**, which are connected to reduced swing clock signals, may have relatively high threshold values. For example, the nfet transistors **858** and **864** that receive on their gate terminals the ClkTop and ClkTopn signals on lines **340** and **346**, respectively, may have a threshold voltage value within the top portion of the full voltage swing. The threshold voltage value may be between half of the voltage supply and the full voltage supply. Similarly, the pfet transistors **852** and **862** may have a relatively high threshold magnitude.

The latch **900** receives the reduced voltage swing clock signals ClkTop on line **340**, ClkBot on line **342**, ClkBotn on line **344** and ClkTopn on line **346**. The latch **900** uses these reduced voltage swing clock signals to maintain a state on Data Out line **106** dependent on a value on the Data In line **102**. As described earlier regarding the clock waveforms in FIG. **5**, the reduced voltage swing clock signals on lines **340-346** may transition from a given voltage level to an intermediate voltage level. Depending on a particular clock signal of the clock signals on lines **340-346**, the given voltage level may be at or near the power supply voltage. Alternatively, depending on the particular clock signal, the given voltage level may be at or near the ground reference. The corresponding voltage range between the given voltage level and the intermediate voltage level may be a fraction of the power supply voltage, or the operational voltage.

Generally speaking, the latch **900** opens and transmits a data value on the Data In line **102**, in response to receiving at least one of the reduced voltage swing clock signals on lines **340-346** at the given voltage level. For example, in response to the transistors **852** and **858** receive a corresponding given voltage level on their respective gate terminals, the latch **900** opens. The latch **900** closes and holds an output data value on the Data Out line **106**, in response to receiving at least one of the reduced voltage swing clock signals on lines **340-346** at the intermediate voltage level. For example, when the tran-

sistors **852** and **858** receive an intermediate value on their respective gate terminals, the latch **900** closes. Further details are provided below.

The transistor **852** has its gate terminal connected to ClkBot on line **342**. The transistor **858** has its gate terminal connected to ClkTop on line **340**. Initially, ClkTop on line **340** may have a logic high value. The signal ClkBot on line **342** may have a logic low value. Therefore, transistors **852** and **858** turn on despite having high thresholds. During this time, an inverted value of a data value on line **102** may be transmitted to the node **868**. The logic value on node **868** is inverted and transferred to the Data Out line **106** through inverter **870**.

The transistors **862** and **864** may also have relatively high threshold voltage values. The transistor **862** has its gate terminal connected to ClkBotn on line **344**. The transistor **864** has its gate terminal connected to ClkTopn on line **346**. Initially, each of ClkBotn and ClkTopn may have a value equivalent to half of the operational voltage. Therefore, the transistors **862** and **864** may be turned off due to their relatively high threshold values.

During a next half of the clock cycle, the signals ClkTop and ClkBot on lines **340** and **342** may transition to a value equivalent to half of the operational voltage. Referring again to FIG. **5**, these waveforms are shown. These waveforms may be produced by circuitry shown in FIG. **6**. The transistors **852** and **858** within the latch **900** may turn off due to their high thresholds. Therefore, further changes on the Data In line **102** may not be propagated to node **868**.

During this same half of the clock cycle, the signal ClkBotn on line **344** may transition to the ground reference. The signal ClkTopn on line **346** may transition to the power supply value. The transistors **862** and **864** may turn on despite their high thresholds. Now the logic value present on the Data Out line **106** may be inverted through transistors **860** and **866** onto node **868**. Thereby, the logic state within the latch **900** is maintained. As shown, no local clock buffers are used, which reduces the power consumed by the latch **900** in addition to utilizing reduced voltage swing clock signals on lines **340-346**.

Turning now to FIG. **9**, a generalized flow diagram illustrating one embodiment of a method **1000** for latching data values using reduced voltage swing clock signals is shown. For purposes of discussion, the steps in this embodiment and subsequent embodiments of methods described later are shown in sequential order. However, in other embodiments some steps may occur in a different order than shown, some steps may be performed concurrently, some steps may be combined with other steps, and some steps may be absent.

In block **1002**, a feedback second stage of a latch may be turned off with reduced swing values on a first set of clock lines. Rather than utilize full swing values, such as a power supply value and a ground reference value used for logic high and low values, a fraction of the operational voltage may be used to turn off the second stage. In one embodiment, the reduced swing value is half of the full swing value of the voltage level. The second stage may be a slave configuration in a master-slave configured latch. The second stage may use high threshold transistors. Therefore, values on the gate terminals equivalent to half of the operational voltage may not turn on these transistors. The first set of clock signals may be provided by a reduced voltage swing clock generator.

In block **1004**, the first stage of the latch may be turned on with full swing values on a second set of clock lines different from the first set of clock lines. At this time, these clock lines may use a power supply value and a ground reference value used for logic high and low values to turn on transistors within

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the first stage. The first stage may be a master configuration within a master-slave configured latch. In block **1006**, any data value on the data input line is propagated through the latch to the data output line, since the first stage is turned on and it's transparent.

In block **1008**, the first stage is turned off with reduced swing values on the first set of clock lines. The first stage may also use high threshold transistors. Therefore, values on the gate terminals equivalent to half of the operational voltage may not turn on these transistors. In block **101**, the feedback second stage of the latch may be turned on with full swing values on the second set of clock lines. The feedback second stage may place an inverted value on an internal node of the value stored on the data output line. The internal node may be inverted and provided on the data output line. This feedback loop maintains the state of the latch. The first and the second stages utilize reduced voltage swings to pass through, load and maintain different states. The use of the reduced voltage swing values reduced power consumption of the latch.

Referring now to FIG. **10**, a generalized block diagram illustrating one embodiment of a clock-gated reduced voltage swing clock generator **1100** is shown. Circuitry and logic shown here similar to circuitry and logic described above are similarly numbered. Similar to the clock generators **600**, **700** and **730**, the generator **1100** receives non-overlapping clock signals on lines **312-318** to provide reduced voltage swing clock signals.

The clock generator **1100** allows clock gating to occur in order to adhere to given power modes that may turn off clock signals. Transistors **1120** and **1122** may be connected as a transmission gate. The control signal ClkStop **1112** may be received on the gate terminal of transistor **1122**. The control signal XClkStop **1114** may be received on the gate terminal of transistor **1120**. During an active mode of operation, the control signal ClkStop **1112** may have a logic low value. In addition, the control signal XClkStop **1114** may have a logic high value. Therefore, the transistors **1120** and **1122** may be turned off and the transmission gate formed by transistors **1120** and **1122** may be in a high impedance state.

In one embodiment, the Input Clock on line **104** may be stopped when it has a logic high value. As a result, Clk2 on line **316** may have a logic high value. The signal Clk2 on line **316** may maintain a logic high value until a falling edge occurs on the Input Clock on line **104**. While Clk2 on line **316** has a logic high value, transistor **614** is turned on. As a result, ClkTop on line **340** is shorted to ClkBot on line **342**. At this time, electrical charge is shared between ClkTop on line **340** and ClkBot on line **342**. The total load capacitance on each of the lines **340** and **342** may be the same. Accordingly, the signals ClkTop and ClkBot may reach a voltage level of approximately one-half of the power supply.

The control signal ClkStop **1112** may rise to a logic high value and turn on the transistor **1122**. The control signal XClkStop **1114** may fall to a logic low value and turn on transistor **1120**. The transmission gate formed by transistors **1120** and **1122** may be on and short ClkTop on line **340** with line **1110**, which is held at a value equivalent to half of the power supply, or operational voltage. The signal ClkBot on line **342** is shorted to ClkTop on line **340** through transistor **614**. Therefore, both ClkTop and ClkBot are held at a value equal to half of the operational voltage while the Input Clock **104** is stopped. In addition, with ClkTop and ClkBot being held at half of the operational voltage, the reduced voltage swing latch **900** maintains its logical state while the Input Clock on line **104** is stopped.

Although the embodiments above have been described in considerable detail, numerous variations and modifications

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will become apparent to those skilled in the art once the above disclosure is fully appreciated. It is intended that the following claims be interpreted to embrace all such variations and modifications.

What is claimed is:

1. A reduced voltage swing clock distribution network comprising:

a clock generator configured to provide a first plurality of clock signals, wherein the first plurality of clock signals are non-overlapping clock signals; and

a reduced voltage swing clock generator, wherein the reduced voltage swing clock generator is configured to: transition a clock signal of at least one of a second plurality of clock signals from a first voltage level to an intermediate voltage level that is between a power supply voltage and a ground reference, in response to detecting a rising edge of a first one of the first plurality of clock signals;

prevent said clock signal from reaching one of the power supply voltage or the ground reference by holding said clock signal at the intermediate voltage level for at least a pulse width of a second one of the first plurality of clock signals; and

transition said clock signal back to the first voltage level in response to detecting a rising edge of a third one of the first plurality of clock signals.

2. The distribution network as recited in claim 1 further comprising a latch coupled to receive the second plurality of clock signals, wherein the latch is configured to:

hold an output data value, in response to receiving at least one of the second plurality of clock signals at the intermediate voltage level; and

transmit a data input value, in response to receiving at least one of the second plurality of clock signals at the first voltage level.

3. The distribution network as recited in claim 1, wherein a given pair of the second plurality of clock signals are on a pair of clock lines with a ratio of loading capacitance that is equal to a ratio of the intermediate voltage level to a difference between the intermediate voltage level and the power supply voltage.

4. The distribution network as recited in claim 3, wherein the given pair of clock lines are shorted together during the pulse width of the second one of the first plurality of clock signals.

5. The distribution network as recited in claim 4, wherein the given pair of clock lines is not connected to the power supply voltage or the ground reference during the pulse width of the second one of the first plurality of clock signals.

6. The distribution network as recited in claim 4, wherein the reduced voltage swing clock generator is further configured to store a portion of an electrical charge on each of the given pair of clock lines on a respective ballast line for reuse later in a clock cycle.

7. The distribution network as recited in claim 4, wherein the reduced voltage swing clock generator is further configured to hold each of the second plurality of clock signals at the intermediate voltage level when an input clock is stopped at a logic high value.

8. The distribution network as recited in claim 5, wherein the reduced voltage swing clock generator is further configured to provide a voltage range for at least one of the second plurality of clock signals between a ground reference and half of the power supply voltage.

9. The distribution network as recited in claim 5, wherein the reduced voltage swing clock generator is further configured to provide a voltage range for at least one of the second

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plurality of clock signals between half of the power supply voltage and the power supply voltage.

10. A method comprising:

providing a first plurality of non-overlapping clock signals; transitioning a clock signal of at least one of a second plurality of clock signals from a first voltage level to an intermediate voltage level that is between a power supply voltage and a ground reference, in response to detecting a rising edge of a first one of the first plurality of clock signals;

preventing said clock level from reaching one of the power supply voltage or the ground reference by holding said clock signal at the intermediate voltage level for at least a pulse width of a second one of the first plurality of clock signals; and

transitioning said clock signal back to the first voltage level in response to a rising edge of a third one of the first plurality of clock signals.

11. The method as recited in claim 10, further comprising: receiving the second plurality of clock signals in a latch; holding an output data value in the latch, in response to receiving at least one of the second plurality of clock signals at the intermediate voltage level; and transmitting a data input value through the latch, in response to receiving at least one of the second plurality of clock signals at the first voltage level.

12. The method as recited in claim 10, wherein a given pair of clock lines has equal loading capacitance.

13. The method as recited in claim 12, further comprising shorting together the given pair of clock lines during the pulse width of the second one of the first plurality of clock signals.

14. The method as recited in claim 13, further comprising storing a portion of a charge on each of the second plurality of clock lines on a respective ballast line for reuse later in a clock cycle.

15. The method as recited in claim 14, further comprising providing a voltage range for a first group of the second plurality of clock signals between a ground reference and half of the power supply voltage and for a second group of the second plurality of clock signals between half of the power supply voltage and the power supply voltage.

16. The method as recited in claim 14, wherein a first group of the second plurality of clock signals are the respective ballast lines for a second group of the second plurality of clock signals, wherein the first group are complement signals of the second group.

17. An apparatus comprising:

circuitry; and

a clock distribution network configured to provide at least one input clock to the circuitry;

wherein the circuitry includes:

an interface to the clock distribution network configured to receive an input clock from the clock distribution network;

a clock generator configured to provide a first plurality of clock signals based upon the received input clock; and

a reduced voltage swing clock generator, wherein the reduced voltage swing clock generator is configured to:

transition a clock signal of at least one of a second plurality of clock signals from a first voltage level to an intermediate voltage level that is between a power supply voltage and a ground reference, in response to detecting a rising edge of a first one of the first plurality of clock signals;

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prevent said clock signal from reaching one of the power supply voltage or the ground reference by holding said clock signal at the intermediate voltage level for at least a pulse width of a second one of the first plurality of clock signals; and

transition said clock signal back to the first voltage level in response to detecting a rising edge of a third one of the first plurality of clock signals.

18. The apparatus as recited in claim 17, wherein a given pair of the second plurality of clock signals are on a pair of clock lines with a ratio of loading capacitance equal to a ratio of the intermediate voltage level to a difference between the intermediate voltage level and the power supply voltage.

19. The apparatus as recited in claim 18, wherein the given pair of clock lines is shorted together during the pulse width of the second one of the first plurality of clock signals.

20. The apparatus as recited in claim 19, wherein the reduced voltage swing clock generator is further configured to store a portion of an electrical charge on each of the given pair of clock lines on a respective ballast line for reuse later in a clock cycle.

21. The apparatus as recited in claim 19, wherein the first plurality of clock signals includes four non-overlapping clock signals, wherein each of the four non-overlapping clock signals is phase shifted 90 degrees from a phase of another of the four non-overlapping clock signals.

22. An integrated circuit comprising:

one or more sequential elements; and

a clock tree configured to provide one or more clock signals to each one of the one or more sequential elements; wherein the clock tree includes:

a clock generator configured to provide a first plurality of clock signals;

a reduced voltage swing clock generator configured to receive the first plurality of clock signals, wherein the reduced voltage swing clock generator is configured to:

transition a clock signal of at least one of a second plurality of clock signals from a first voltage level to an intermediate voltage level that is between a power supply voltage and a ground reference, in response to detecting a rising edge of a first one of the first plurality of clock signals;

prevent said clock signal from reaching one of the power supply voltage or the ground reference by holding said clock signal at the intermediate voltage level for at least a pulse width of a second one of the first plurality of clock signals; and transition said clock signal back to the first voltage level in response to detecting a rising edge of a third one of the first plurality of clock signals.

23. The integrated circuit as recited in claim 22, wherein a given pair of the second plurality of clock signals are on a pair of clock lines with a ratio of loading capacitance equal to a ratio of the intermediate voltage level to a difference between the intermediate voltage level and the power supply voltage.

24. The integrated circuit as recited in claim 23, wherein the given pair of clock lines is shorted together during the pulse width of the second one of the first plurality of clock signals.

25. The integrated circuit as recited in claim 24, wherein the reduced voltage swing clock generator is further configured to provide a voltage range for a first group of the second plurality of clock signals between a ground reference and half of the power supply voltage and for a second group of the

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second plurality of clock signals between half of the power supply voltage and the power supply voltage.

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